Monsanto

June 1996

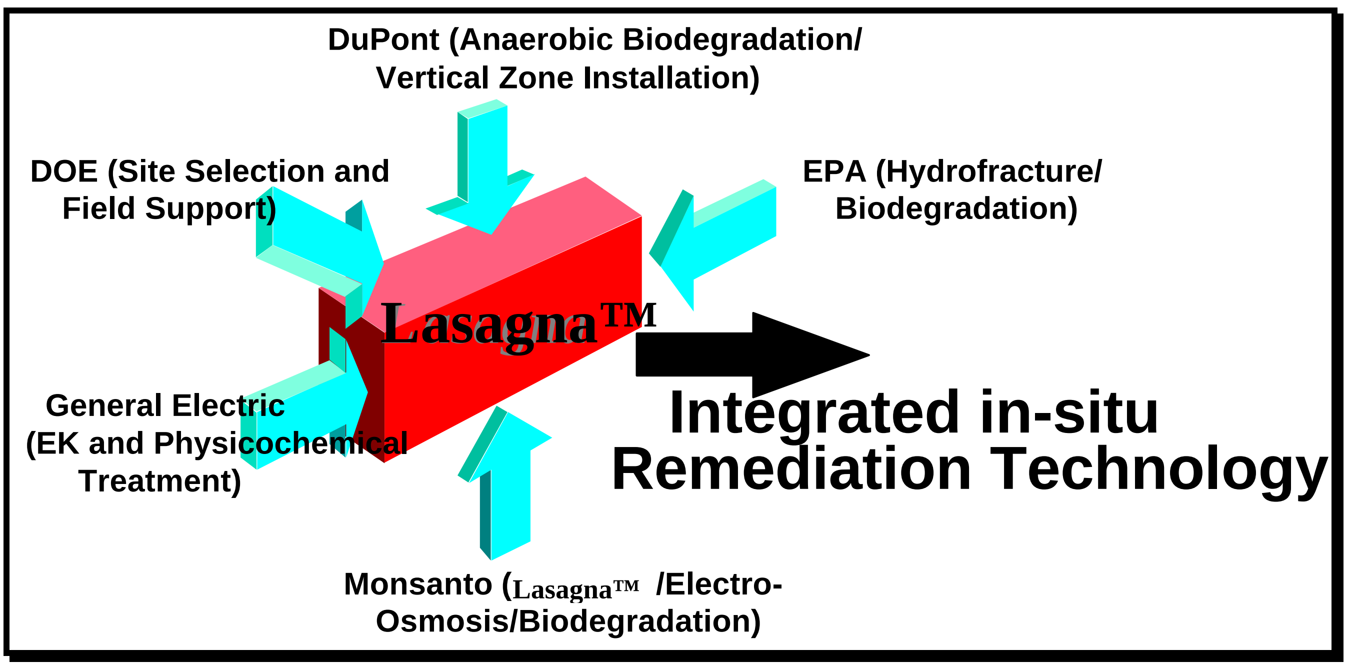
Development of an Integrated *in-situ* Remediation Technology

Topical Report for *Task No. 5 entitled "Cost Analysis"*

(September 26, 1994 - May 25, 1996)

Gary Quinton, Dale Schultz, Richard Landis, Ronald Griffith, and Stephen Shoemaker (DuPont Company)

DOE Contract Number: DE-AR21-94MC31185



Submitted to:
U. S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

Submitted by:
Dupont Company
Wilmington, DE 19805

and

Monsanto Company
800 N. Lindbergh Boulevard
St. Louis, Missouri 63167

Monsanto

"The Key to Environmental Safety"

Monsanto Company
800 N. Lindbergh Boulevard
St. Louis, Missouri 63167
Phone: (314) 694-1466
FAX: (314) 694-1531

20 March, 1997

Re: Ordering Information for *"Development of an Integrated in-situ Remediation Technology"* Topical Reports generated under DOE contract number DE-AR21-94MC31185 which was signed September 26, 1994.

Dear Sir/Ms.:

The following table summarizes ordering information for all technical reports written for the above referenced contract. Copies of these reports may be obtained from the Office of Scientific and Technical Information [(423)576-8401] if you are with DOE or a DOE contractor, or from:

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161
Phone: (703)487-4600 (Regular Service)
Phone: (703)487-4700 (Rush Service, $10.00 Additional Per Item)

(continued on next page)

Title	Document Number
• **Topical Report for Task #1 entitled "Evaluation of Treatment Zone Formation Options" (September 26, 1994 - May 25, 1996)** Stephen H. Shoemaker, Richard C. Landis, Ronald J. Griffith, Dale S. Schultz, and Gary E. Quinton (DuPont Company)	**DOE/METC/31185 —5436, DE97002165**
• **Topical Report for Tasks #2-4 entitled "Electrokinetic Modeling" (September 26, 1994 - May 25, 1996)** Andrew P. Shapiro (General Electric Company)	**DOE/METC/31185 —5391, DE97002135**
• **Topical Report for Task #5 entitled "Cost Analysis" (September 26, 1994 - May 25, 1996)** Gary Quinton, Dale Schultz, Richard Landis, Ronald Griffith, and Stephen Shoemaker (DuPont Company)	**DOE/METC/31185 —5389, DE97002134**
• **Topical Report for Task #6 entitled "Lab-Scale Development of Microbial Degradation Process" (September 26, 1994 - May 25, 1996)** J. Martin Odom (DuPont Company)	**DOE/METC/31185 —5388, DE97002130**
• **Topical Report for Task #7 entitled "Development of Degradation Processes" (September 26, 1994 - May 25, 1996)** M. J. Brackin, M. H. Heitkamp and S. V. Ho (Monsanto Company)	**DOE/METC/31185 —5495, DE97002165**
• **Topical Report for Tasks #8 and 10 entitled "Laboratory and Pilot Scale Experiments of the *Lasagna*™ Process" (September 26, 1994 - May 25, 1996)** Sa V. Ho, Christopher J. Athmer, and P. Wayne Sheridan (Monsanto Company) and Andrew P. Shapiro (General Electric Company)	**DOE/METC/31185 —5375, DE97002150**
• **Topical Report for Task #9-Part I entitled "TCE Degradation Using Non-Biological Methods" (September 26, 1994 - May 25, 1996)** Andrew P. Shapiro, Timothy M. Sivavec, and Sunita S. Baghel (General Electric Company)	**DOE/METC/31185 —5392, DE97002133**
• **Topical Report for Task #9 - Part II entitled "TCE Degradation Using Non-Biological Methods" (September 26, 1994 - May 25, 1996)** Robert G. Orth and David E. McKenzie (Monsanto Company)	**DOE/METC/31185 —5393, DE97002131**

(continued on next page)

• **Topical Report for Task #11 entitled "Evaluation of TCE Contamination Before and After the Field Experiment" (September 26, 1994 - May 25, 1996)** B. Mason Hughes, Sa V. Ho, Christopher J. Athmer, and P. Wayne Sheridan (Monsanto Company) Stephen H. Shoemaker and John R. Larson (DuPont) Jay L. Clausen (LMES) and John L. Zutman (ORNL-Grand Junction)	**DOE/METC/31185—5496, DE97002166**
• **Topical Report for Tasks #12 and 13 entitled "Large Scale Field Test of the *Lasagna*™ Process" (September 26, 1994 - May 25, 1996)** Christopher J. Athmer, Sa V. Ho, B. Mason Hughes, P. Wayne Sheridan, and P. H. Brodsky (Monsanto Company) Andrew P. Shapiro, Roy F. Thornton, and Joseph J. Salvo (General Electric Company) and Dale S. Schultz, Richard C. Landis, Ron Griffith, and Stephen H. Shoemaker (DuPont)	**DOE/METC/31185—5390, DE97002156**

A. Executive Summary

Development of an Integrated *In Situ* Remediation Technology

DOE Contract Number: DE-AR21-94MC31185

Topical Report for *Task #5: Cost Analysis*

Gary Quinton, Dale Schultz, Richard Landis, Ronald Griffith, and Stephen Shoemaker

Submitted by:
DuPont Company
Barley Mill Plaza
Lancaster Pike and Rt. 141
Wilmington, DE 19805

and

Monsanto Company
St. Louis, Missouri

Abstract: Contamination in low permeability soils poses a significant technical challenge to in situ remediation efforts. Poor accessibility to the contaminants and difficulty in delivering treatment reagents have rendered existing in situ treatments such as bioremediation, vapor extraction, pump and treat rather ineffective when applied to low permeability soils present at many contaminated sites. The Lasagna™ technology is an integrated in situ treatment in which established geotechnical methods are used to install degradation zones directly into the contaminated soil and electro-osmosis is utilized to move the contaminants back and forth through those zones until the treatment is completed. This topical report presents the results of an engineering evaluation and cost analysis of the vertically configured treatment process completed by the DuPont Company. The cost evaluation was prepared by developing a cost optimization model of the overall treatment process. This model considers various input parameters such as soil properties, depth of contamination, cost for emplacing electrodes and treatment zones, required purge water volume, time constraints to achieve cleanup, and cost of power. Several example cases were run using the cost model to provide representative cost ranges for applying the technology to clean up trichloroethene contamination in clay. These costs are estimated to range from $40 to $95 per cubic yard of soil for a 1-acre site, with cost depending on depth of contamination (cost range valid from 15 to 45 ft), method of electrode/treatment zone emplacement (cost range valid for Lasagna™ Phase I emplacement and optimized emplacement techniques), and time available to complete remediation (cost range valid for one- and three-year timeframe).

B. Acronyms and Abbreviations

A	cross-sectional area to perpendicular flow
α	pore volumes, dimensionless
C	total cost of remediation, $
C_E	electrode cost, excluding mobilization cost, $
C_e	electrical energy cost, $
C_F	fixed costs, $
D	installation depth, ft
E	electrical field gradient, V
E_{max}	maximum field gradient, V/M
Fe	iron
GE	General Electric Company
k_e	electro-osmotic permeabiilty, $cm^2/V \cdot s$
Ir	iridium
ISTZ	in situ treatment zone
L_e	distance between electrode zones, m or ft
L_T	distance between treatment zones, m or ft
n	soil porosity, vol/vol (dimensionless)
N_E	number of electrode rows (dimensionless)
N_T	number of treatment zone rows (dimensionless)
O	oxygen
P_E	price of installed electrode, $\$/ft^2$
P_e	price of electricity, $/kWH
P_T	price of installed treatment zone, $\$/ft^2$
Q	electro-osmotic flow rate, m^3/S
σ	soil electrical conductivity, mS/cm
T	remediation time, yrs
V_{max}	maximum potential, V
X	site width, ft
Y	site length, ft

C. Units

cm	centimeters
sq cm	square centimeters
cu yd	cubic yards
ft	feet
g	grams
gal	gallons
gpm	gallons/minute
hr	hour(s)
in.	inches
kW	kilowatt
kWH	kilowatt-hour
lb, lbs	pound(s)
m	meter
mS/cm	milliSiemen/centimeter
sq ft	square foot
yr(s)	year(s)

D. Table of Contents

List of Tables

(page)

List of Figures

E. Background

Statement of the Problem

Contamination in low permeability soils poses a significant technical challenge to *in situ* remediation efforts. Poor accessibility to the contaminants and difficulty in delivery of treatment reagents have rendered existing *in situ* treatments such as bioremediation, vapor extraction, and pump and treat, rather ineffective when applied to low permeability soils present at many contaminated sites.

The Solution

The proposed technology combines electro-osmosis with treatment zones that are installed directly in the contaminated soils to form an integrated *in situ* remedial process. Electro-osmosis is an old civil engineering technique and is well known for its effectiveness in moving water uniformly through low-permeability soils with very low power consumption.

Conceptually, the integrated technology could treat organic and inorganic contamination, as well as mixed wastes. Once developed, the technology will have tremendous benefits over existing ones in many aspects including environmental impacts, cost effectiveness, waste generation, treatment flexibility, and breadth of applications.

Consortium Description

A Consortium has been formed consisting of Monsanto, E. I. du Pont de Nemours & Co., Inc. (DuPont) and General Electric (GE), with participation from the Environmental Protection Agency (EPA) Office of Research and Development and the Department of Energy (DOE) Environmental Management Office of Science and Technology. The five members of this group are leaders in their represented technologies and hold significant patents and intellectual property which, in concert, may form an integrated solution for soil treatment. The Consortium's activities are being facilitated by Clean Sites, Inc., under a Cooperative Agreement with EPA's Technology Innovation Office. A schematic diagram of the government/industry consortium is shown on the front page of this topical report.

Management Plan

A Management Plan for this project was prepared by Monsanto and submitted on November 30, 1994. That plan summarized the work plan which was developed in conjunction with DuPont, GE, EPA's Risk Reduction Engineering Laboratory (RREL), Martin Marietta Energy Systems (MMES), and the Department of Energy. The DOE Gaseous Diffusion Plant in Paducah, Kentucky, has been chosen as the site for the initial field tests.

CDM Federal Programs Corporation was chosen to provide the on-site support of the field tests which were installed at the DOE site in November 1994. This experiment tested the combination of electro-osmosis and *in situ* sorption in the treatment zones. In 1994 and 1995, technology development was carried out under the present contract by Monsanto, DuPont, and GE. These studies evaluated various degradation processes and their integration into the overall treatment scheme at bench and pilot scales.

Technical Deliverables

Tables 1 and 2 summarize the 13 technical tasks and the 8 topical reports which will be written describing the results obtained in the technical tasks. These two tables show which organization is primarily responsible for the tasks and for preparing the topical reports. The present topical report summarizes Task #5 - Cost Analysis.

Table E-1. List of Tasks and Responsible Company

Task	Company
Task 1 - Evaluation of Treatment Zone Formation Options (5.1.2)	DuPont
Task 2 - Electrokinetic Model Validation and Improvement (6.5)	GE
Task 3 - Design Guidance for Field Experiments (6.6)	GE/DuPont
Task 4 - Analysis of Electrode Geometry and Soil Heterogeneity (6.7)	GE/DuPont
Task 5 - Cost Analysis (7)	Monsanto/DuPont
Task 6 - Lab-Scale Development of Microbial Degradation Process (8.1.2)	DuPont
Task 7 - Lab-Scale Electrokinetic and Microbial Degradation (8.1.6)	Monsanto
Task 8 - Lab-Scale Tests of Lasagna Process Using DOE Paducah Soil (8.1.7)	Monsanto
Task 9 - TCE Degradation Using Non-Biological Methods (8.2.1, 8.2.2.2, 8.2.3.2)	GE/Monsanto
Task 10 - Bench- and Pilot-Scale Tests (9.3)	Monsanto
Task 11 - Establish Contamination Conditions Before and After Tests (10.1.2)	DuPont/MMES
Task 12 - Design and Fabrication of Large-Scale Lasagna Process (12.1, 12.2)	Monsanto/DuPont/Nilex
Task 13 - Large-Scale Field Test of Lasagna Process (12.3, 12.4)	Monsanto/CDM

Table E-2. List of Topical Reports and Responsible Company

Topical Report	Company
Task 1 - Evaluation of Treatment Zone Formation Options	DuPont
Tasks 2 - 4 Electrokinetic Modeling	GE
Task 5 - Cost Analysis	DuPont
Task 6 - Laboratory-Scale Microbial Degradation	DuPont
Tasks 7, 8, 10 - Bench- and Pilot-Scale Tests of Lasagna Process	Monsanto
Tasks 9 - TCE Degradation Using Non-Biological Methods	GE
Task 11 - Contamination Analysis, Before and After Treatment	Monsanto
Tasks 12 and 13 - Large-Scale Field Test of Lasagna Process	Monsanto

F. Topical Report for Task #5

1.0 INTRODUCTION AND PURPOSE

1.1 Layered Remediation Process (Lasagna™)

Contamination in low permeability, clayey soils poses a significant technical challenge to *in situ* remediation efforts. Poor accessibility to the contaminants and difficulty in delivering treatment reagents make traditional, cost-effective *in situ* methods, such as bioremediation and soil vapor extraction, ineffective for clayey soils.

The Lasagna™ process seeks to address these limitations. Lasagna™ is an integrated *in situ* treatment in which established geotechnical methods are used to install degradation zones directly into the contaminated soil, and electro-osmosis is used to move the contaminants to and through these zones to complete the treatment *in situ*. Electro-osmosis is a classical civil engineering technique well known for its effectiveness in dewatering low-permeability soils. Conceptually, the integrated technology could treat a range of contaminants, including organics and inorganics.

The general approach of Lasagna™ can be summarized as follows:

- Create treatment zones in close proximity sectioned through the contaminated soil region by emplacing appropriate materials, such as sorbents, catalytic agents, microbes, oxidants, etc., chosen to fit the given contaminant(s). Hydraulic fracturing and related technologies may provide an effective and low-cost means for creating such zones horizontally in the soil. The treatment zones also can be placed in a vertical configuration.

- Use electro-osmosis as a liquid pump for flushing contaminants from the soil into the treatment zones. Since these zones are spaced closely, contaminants can be moved from one zone to the next in a short time. In the horizontal configuration, the zones above and below the contaminated soil region can be injected with graphite particles or other conductive material to form electrodes in place. Similarly, vertically oriented electrodes can be installed using standard geotechnical practices such as steel sheet pile installation.

- Reverse liquid flow by switching electrical polarity to effect multiple passes of the contaminants through the treatment zones for complete sorption/destruction. This step also can minimize complications associated with the long-term application of one-directional electro-osmotic processes (for example, development of osmotic and pH gradients, soil drying, and mineral precipitation).

In the typical application of electro-osmosis, water introduced into the soil at the anode region flows under electro-osmosis through the contaminated soil, flushing the contaminants to the cathode region for extraction and treatment aboveground.

Major advantages for electro-osmosis include:

- Flow distribution will be uniform in low permeability or heterogeneous soil because flow rate is independent of pore size.

- Flow direction and rates can be controlled by the placement of electrodes and applied voltage.

- Power consumption is relatively low.

Electro-osmotic flow velocities are slow, usually on the order of 2 cm per day or less for most soils under typical voltage gradients. The slow rate limits the practical spacing between anode and cathode, since flow must be driven all the way between electrodes to effect contaminant removal. The electrode spacing affects not only the time required to complete cleanup, but also the power requirements and, ultimately, the cleanup cost. Based on an economic model for the electro-osmotic soil flushing process using planar electrode systems discussed in this report, the cost-optimized electrode spacing is on the order of 3 to 6 m for most soils. This spacing allows cleanup within a reasonable time frame (for example, less than five years), while avoiding soil overheating. The model also has been used to predict that electrode construction would be a significant portion of the overall application cost of the optimized process, generally on the order of 20 to 40%.

As discussed above, the Lasagna™ process places treatment zones between the electrodes to reduce this electrode spacing limitation. Conceptually, this reduces cleanup time and power input, since contaminants must be transported only between treatment zones, rather than the electrodes. If one assumes that it is less expensive to install treatment zones than electrode systems, a substantial cost benefit may be realized. Whether a horizontal or vertical configuration is chosen, the ability to emplace treatment zones and electrodes in the soil in relatively close spacing and at reasonable cost is critical to the cost effectiveness of the technology.

1.2 Purpose of Cost Analysis

The goals of the analysis presented here were to:

- Estimate the three key parameters of a Lasagna™ project.
  - number of electrode rows
  - number of treatment zones per electrode pair
  - the applied electrical potential

- Use those values to perform a detailed cost analysis.

The three parameters greatly affect the cost of the operation. Section 2.1 of this report discusses a cost model based on these parameters, which can be used to determine the design that minimizes cost. Based on these results, Section 2.2 presents implementation cost estimates for three emplacement technologies. See Topical Report No. 1 for additional discussion of the treatment zone and electrode cost elements.

2.0 COST ANALYSIS

2.1 Cost Model

The costs of an electro-osmotic remediation project are divided into three categories:

- Electrode and treatment zone materials and installation.
- Electricity.
- Fixed costs.

Fixed costs include those for the rectifier and power control system, the fluid-handling system, mobilization of equipment to install the electrodes and treatment zones, maintenance, etc.

2.1.1 Installing Electrodes and Treatment Zones

Suppose that N_E equally spaced electrode rows are installed in a site of length Y. This divides the site into (N_E-1) electrode pairs, with spacing between electrode rows (L_E) equal to Y/(N_E-1). If N_T treatment zone rows are equally spaced within the region of each electrode pair, then the spacing between treatment zones (L_T) is

$$L_T = \frac{Y}{(N_T + 1)(N_E - 1)} \qquad (1)$$

The cost for installing rows of electrodes and treatment zones may be expressed as the sum of equipment mobilization expenses (treated here as fixed cost) and costs that are proportional to the area of the installed materials.

The electrode cost excluding mobilization costs (C_E) is

$$C_E = P_E N_E D X \qquad (2)$$

where P_E is the price of electrode material and installation on a per-area basis, D is the installation depth, and X is the width of the site.

Similarly, the treatment zone cost exclusive of mobilization (C_T) is

$$C_T = P_T N_T (N_E - 1) DX \tag{3}$$

where P_T is the price of treatment zone material and installation on a per-area basis.

2.1.2 Electricity Costs

The cost of electricity may be expressed as:

$$C_e = P_e \text{ (Soil Volume) (Power Input per Soil Volume) (Remediation Time)} \tag{4}$$

where C_e is the electrical energy cost per soil volume and P_e is the price of electricity (e.g., in \$/kWH).

The power input per soil volume is

$$\frac{\text{Power Input}}{\text{Soil Volume}} = \sigma E^2 \tag{5}$$

where σ is the soil electrical conductivity and E is the electrical field gradient. Therefore, the electricity cost is

$$C_e = P_e DXY\sigma E^2 T \tag{6}$$

where T is the remediation time. The process must continue for enough time to drive the required purge water volume through the soil:

$$T = \frac{\text{Required Purge Water Volume}}{\text{Electroosmotic Flowrate}} \tag{7}$$

For the soil between a pair of treatment zones separated by distance L_T,

$$\text{Required Purge Water Volume} = \alpha n A L_T \tag{8}$$

where α is the required number of pore volumes to adequately clean the soil, n is the soil porosity (vol/vol), and A is the cross-sectional area perpendicular to flow. The number of pore volumes is determined through laboratory testing of the soil to meet restoration goals. The electro-osmotic flowrate (Q) is given by

$$Q = k_e A E \tag{9}$$

where k_e is the electro-osmotic permeability.

Combining Equations 7 - 9 yields an expression for the remediation time in terms of the applied voltage and the treatment zone separation distance:

$$T = \frac{\alpha n L_T}{k_e E} \tag{10}$$

which may be rearranged to yield

$$E = \frac{\alpha n L_T}{k_e T} \tag{11}$$

Combining Equations 2, 3, and 4, the total cost of the remediation project (C) is

$$C = P_E N_E DX + P_T N_T (N_E - 1) DX + P_e DXY\sigma E^2 T + C_F \tag{12}$$

where E is given by Equation 11 and C_F represents fixed costs.

2.1.3 Fixed Costs

The fixed cost elements in this cost model were estimated using a variety of cost-estimating sources. The items described below are for the installed process equipment with all ancillaries needed for complete process operation. Expenses for items such as piping, instrumentation, power control and distribution, fluid handling, as well as mobilization and demobilization of the emplacement equipment have been "fixed" in this analysis. The annual maintenance cost was factored from the fixed investment.

- Data acquisition systems:

  $25,000 based on Paducah system cost. Data acquisition systems (power control /computer control) are estimated to be between $15,000 and $30,000, based on DuPont experience. This price includes telemetry by data line.

- Electrical distribution:

  Assumption — Line power is available. Cost of overhead distribution is **$7,000** based on a 200-ft run of powerline and poles. The use of diesel generators versus line power is discussed below.

- Mobilization and demobilization:

Assuming that the Nilex drive system is used for one month, the mobilization of the Nilex equipment is $6,000, and the associated excavator to drive the equipment is $14,000 (including local mobilization and demobilization) for the month. The total for system mobilization is **$20,000**.

- Fluid handling system:

Assuming two tanks (anode and cathode) at 500 gal and associated pumps, piping and agitators, a reasonable estimate is **$60,000**. This estimate is based on DuPont experience with tank installations. Ancillary equipment cost is based on the fluid handling sub-system at the DuPont Spruance site electro-osmosis pilot. It is assumed that this installation does not need to be housed in a building.

- Maintenance cost:

Assume 20% of the cost of fluid handling system, power control system (e.g., thermocouples burn out), and power distribution system (e.g., loose wiring, fittings). Assume a four-year remediation at a maintenance cost of $18,400 per year, or **~$74,000**.

- SUBTOTAL COST:

Data Acquisition	$ 25,000
Electrical Distribution	7,000
Mobilization/demobilization	20,000
Fluid handling system	60,000
Maintenance (4 yrs)	74,000
• SUBTOTAL	$186,000
Contingency (35%)	64,000
• TOTAL FIXED COSTS	$250,000

An engineering analysis was conducted on the cost of diesel-generated power versus the purchase of line power at $0.05 per kWH. In general, the diesel generator costs are somewhat insensitive for the 100-400 kWH delivery range. This spread is from $30,000 to $40,000 for a purchased and installed unit. Monthly lease rates were very sensitive to power delivered and range in cost from $1150 (15 kW) to $1695 (50 kW). Since most remediations will take two to five years, the purchase option is best for the diesel generator, if line power is not available. The drawback to generating one's own power is that the diesel generator must be serviced. Annual operating and maintenance (O&M) costs may be significant.

Diesel fuel will deliver approximately 25 kWH/gal. If diesel fuel costs $1.25/gal, the cost of power is $0.05 per kWH. This operational cost must be added to the rental or purchase cost of the diesel generator.

Except in locations where the cost of electrical line power would exceed that of diesel generator installation plus O&M, the least-cost alternative is to use continuous electrical feed.

2.1.4 Strategy

Using the cost model developed in Section 2.1, a strategy can be developed to determine the design that minimizes cost. The goal is to select the number of electrode rows (N_E) and treatment zones per electrode pair (N_T) that reduce the total cost (C). Two additional constraints may be important. First, the cost-minimum design suggested by Equation 12 may require an electric field strength that would overheat the soil. So it is important to consider only those N_E-N_T combinations for which the resulting field gradient calculated by Equation 11 is less than some maximum value (E_{max}). Second, it is possible that the total applied potential that is calculated (the product of E and the electrode spacing) would be higher than acceptable from a safety standpoint. So an additional constraint would be to insist that $\Delta V \leq \Delta V_{max}$.

With these constraints, the strategy for determining the proper design is:

1. Specify
   - Site and soil properties (D, X, Y, α, k_e, σ, n)
   - Prices of supplies and services (P_e, P_E, P_T, C_F)
   - Remediation Time (T)
2. Trying different values of N_E and N_T, calculate:

$$E = \frac{\alpha n L_T}{k_e T} \tag{11}$$

where:

$$L_T = \frac{Y}{(N_T + 1)(N_E - 1)} \tag{1}$$

$$C = P_E N_E DX + P_T N_T (N_E - 1) DX + P_e DXY\sigma E^2 T + C_F \tag{12}$$

$$\Delta V = \frac{\alpha n L_T L_E}{k_e T}$$

where:

$$L_E = \frac{Y}{N_E - 1}$$

3. Select the N_E-N_T pair that minimizes C while maintaining

$$E \leq E_{max} \quad \text{and} \quad \Delta V \leq \Delta V_{max}$$

2.1.5 Examples

The following parameters were used to test the strategy outlined above:

D	20 ft
X	209 ft
Y	209 ft
k_e	1.5 x 10^{-5} cm^2 V^{-1} s^{-1}
σ	0.3 mS/cm
α	2 to 8
P_e	\$0.05/kWH
P_E	\$20/ft^2
P_T	\$10/ft^2
C_F	\$250,000

T	1 to 4 years
E_{max}	50 volt/m
V_{max}	200 volts

The resulting costs ranged from $50/cu yd for a four-year remediation project requiring two pore volumes of flow to $173/cu yd for a one-year remediation project requiring eight pore volumes of flow (Figure F-1).

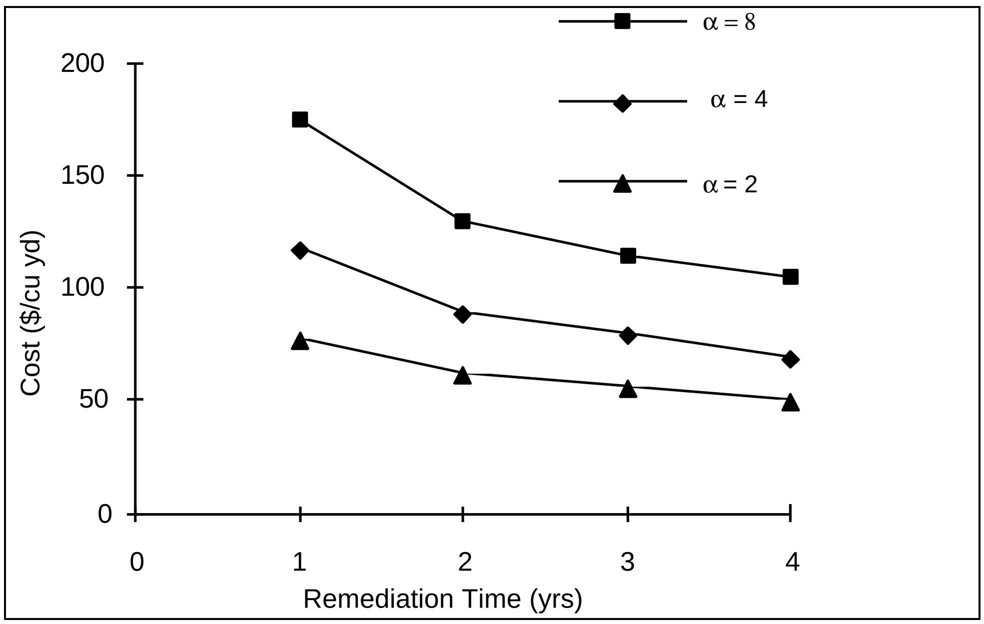


Figure F-1. Generic Parameters Vertical Lasagna Cost Estimates: Effects of Time and No. Pore Volumes

Each of the data points in Figure F-1 represents a N_E-N_T combination that minimized the cost while maintaining E less than 50 volt/m and ΔV less that 200 volts. The values of other calculated quantities are given below.

a	**T (yrs)**	$\mathbf{N_E}$	$\mathbf{N_T}$	**E (volt/m)**	**ΔV (volt)**	$\mathbf{L_T}$ **(ft)**
2	1	12	2	33	189	6.3
	2	9	2	23	179	8.7
	3	6	4	14	183	8.4

	4	6	3	14	172	10.5
4	1	15	3	39	175	3.7
	2	12	2	33	189	6.3
	3	9	3	23	179	6.5
	4	7	4	18	196	6.0
5	1	15	6	44	200	2.1
	2	13	4	36	191	3.5
	3	11	4	29	183	4.2
	4	8	6	22	200	4.3

2.1.6 Conclusion

Many factors influence the proper design of a remediation project. The examples given here are meant merely to indicate general trends. They suggest that if a relatively small amount of time is allotted for the project, the treatment zones will have to be more closely placed and the resulting cost considerably higher.

2.2 Lasagna Implementation Cost Estimate

Several emplacement technologies and their associated costs are discussed in the Topical Report No. 1, "Evaluation of Vertical Treatment Zone Formation Options." Refer to that document for detailed information; costs for the options considered in that report are summarized in Figure F-2.

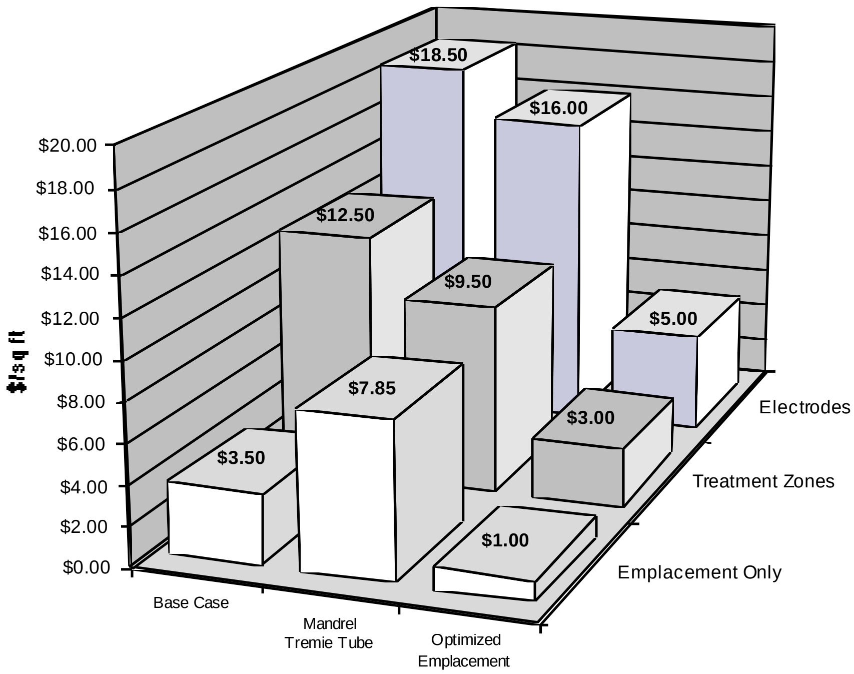


Figure F-2. Emplacement Cost Summary

The cost evaluation discussed in this Task 5 report was performed only for those methods that were considered economically feasible:

- Base case, which was the Phase I Lasagna electrode material (steel plate with wickdrain and a carbon-filled treatment zone
- Mandrel tremie tube, uses an electrode composed of an iron/carbon mixture and an iridium-oxide-coated titanium mesh and a clay/iron treatment zone.
- An "optimized emplacement" case in which a hypothetical case was developed for a $5/sq ft electrode and a $3/sq ft treatment zone.

An engineering evaluation of the cost-optimized placement of the electrodes and zones was conducted, and the results of this study are presented in Table F-1.

Table F-1 Summary of Emplacement Methods and Vertical Layered Remediation Costs							
			One-Year Cases				
Emplacement Method	**Electrode/ ISTZ ($/ft^2)**	**Depth (ft)**	**A/C Dist (ft)**	**TZ Dist (ft)**	**Field Poten. (volts)**	**Grad (v/m)**	**Cost ($/yd^3)**
Base Case	18.50/12.50	15	26.3	5.3	217	27.1	93
	18.50/12.50	45	26.3	5.3	217	27.1	86
Mandrel Tremie Tube	16.00/9.50	15	52.5	6.6	542	33.9	71
	16.00/9.50	45	52.5	6.6	542	33.9	63
Optimized	5.00/3.00	15	42.0	4.7	308	24.1	38
Emplacement	5.00/3.00	45	42.0	4.7	308	24.1	31
			Three-Year Cases				
Base Case	18.50/12.50	15	70.0	11.7	428	20.1	59
	18.50/12.50	45	70.0	11.7	428	20.1	50
Mandrel Tremie Tube	16.00/9.50	15	52.5	10.5	289	18.1	53
	16.00/9.50	45	52.5	10.5	289	18.1	44
Optimized	5.00/3.00	15	52.5	7.5	206	12.9	31
Emplacement	5.00/3.00	45	52.5	7.5	206	12.9	22

All cases assume that the areal extent of contamination is 1 acre. The contamination was assumed to occur 15 and 45 ft below the surface. Duration of remedial activity was assumed to be one or three years. The number of soil pore volumes flushed (parameter known as alpha) over that time frame was set to 2. For the three-year cases, a discount rate of 12% was used to develop present costs for labor and electricity used over multiple years. Other site-specific parameters used in the model may be found in Appendix A. A sensitivity analysis to a 6% and a 12% discount rate was performed on the cost of labor and electricity. The lower discount rate adds less than $1 to the cost per yard on a present cost basis.

2.2.1 Base case (Phase I electrode material)

The first emplacement technology uses the Phase I Lasagna™ electrode material (steel plate with a 1 in. wickdrain), and an *in situ* treatment zone (ISTZ) of a 1 in. wickdrain filled with carbon. This is called the Base Case. This emplacement technology is well defined and was field piloted. (The details on these materials may be found in the Task 1 Report, Section 2.2.1.5.) The cost per installed square foot is $18.50 for the electrode material and $12.50 for the ISTZ. The technology implementation cost for the one-year case is $80 to $95/cu yd, and the cost for the three-year case is $50 to $60/cu yd, depending on depth of contamination.

2.2.2 Mandrel tremie tube

The second emplacement technology uses electrodes composed of an iron/carbon mixture and an iridium-oxide-coated titanium mesh. The ISTZ is 20% iron, 80% clay. The respective installed costs of these emplacements are $16.00 and $9.00/sq ft. The technology implementation cost for the one-year case is $60 to $70/cu yd, and the cost for the three-year case is $40 to $50/cu yd, depending on depth of contamination.

Mandrel-based emplacement using a static or vibratory driving technique is commonly used to install wick drains for soil consolidation. The technique is similar to standard techniques used to drive sheet piles except that a tubular steel mandrel is driven into the ground in place of the sheet piling. A typical mandrel for wick drain emplacement has a small cross-sectional area (typical mandrel dimensions are 2 in. by 5 in.), which provides sufficient interior sleeve space to insert the standard 4-inch vertical wick drain. The typical rig used in this process includes a modified excavator or crane, a mast similar to that of a drilling rig, a vibratory hammer, and a mandrel assembly. The size of the equipment (e.g., mast size, vibratory hammer size) is selected based on the soil conditions and depth of emplacement. Wick drains have been emplaced to depths up to 190 ft using this technique. However, the depth that can be achieved is a function of the soil density and vibratory hammer size, and cobbles, debris, or other impenetrable materials can cause the mandrel to meet refusal. A vibratory hammer drives the mandrel into the soil until the desired depth is reached. The drive shoe/anchor prevents soil from entering the mandrel during emplacement and securely anchors the wick drain in the soil at the desired depth. The mandrel is then extracted.

If a loose emplacement approach is sufficient or more cost effective, the treatment materials can simply be poured or pumped into the mandrel after it is driven into the ground. This techniuqe has been termed the “tremie tube” method. As the mandrel is extracted, the treatment zone materials fill the void created in the soil by the mandrel. To emplace electrodes in a loose manner, electrode material (and if needed, geomembrane material) is placed into the mandrel, and the remaining volume is filled with treatment zone material or filler material. Again, as the mandrel is extracted, the electrode, geomembrane, and treatment zone materials fill the created void in the soil.

As discussed in the Task 1 Report, Sections 2.2.1.3 through 2.2.1.5, this technology will require some development.

2.2.3 Optimized Emplacement

The third emplacement technology is a hypothetical case, which studies the cost reduction incentive for further developing “advanced” Lasagna™ materials. The case considers our estimated lowest feasible cost for electrodes and treatment zones using mass-produced, prefabricated materials emplaced by the mandrel technology (i.e., wick drain emplacement). Under this specific case, the bi-directional electrodes and treatment zones consist of conductive steel mesh and granular iron, respectively, sandwiched within a 1/4-inch thick wick drain. Key assumptions are:

- The prefabricated materials would be no more expensive to manufacture than standard wick drains (allowing for additional cost of materials).
- These prefabricated materials could be emplaced as efficiently and as cheaply as standard wick drains using the mandrel approach.

Total estimated costs of electrodes and treatment zones, including materials and emplacement, are $5.00 and $3.00/sq ft, respectively. These values do not include equipment mobilization or demobilization costs.

The technology implementation cost for the one-year case is $30 to $40, depending on depth of contamination, and the cost for the three-year case is $20 to $30, depending on depth of contamination.

2.2.4 Conclusion

If a remedial action must be completed within a year, the implementation cost of the vertical layered remediation method ranges from around $60 to about $90/cu yd, depending on the emplacement technique and depth of contamination. In general, deeper contamination, although involving more technically challenging emplacement, costs less due to the larger volumes remediated per square foot of electrode.

Given a three-year remediation time, the implementation cost of the vertical layered remediation method ranges from $40 to $70/cu yd, depending on the emplacement technique and depth of contamination.

DuPont has benchmarked a number of *in situ* technologies over the last three years. These technologies include *in situ* treatment zones utilizing iron filings for dehalogenation of chlorinated solvents, pump and treat of contaminated groundwater, *in situ* anaerobic biological dechlorination, surfactant flushing, and vertical layered remediation (Lasagna™). The results show that the costs for these technologies, some of which require more than 30 years to remediate a site, are between $25 and $75/cu yd.

The net present cost method was used for remediations requiring multiple years (discount rate of 12%).

Our analysis of the layered remediation method shows that this *in situ* technology falls in the range of the competing technologies, with an implementation cost over three years of approximately $50/cu yd using the mandrel tremie tube method. This method of emplacement needs some development, but is considered to be implementable in the future.

APPENDIX A
TABLE OF CONTENTS

Exhibit 1. Base Case (1 Yr, 15 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$18.50**	$/ft2	199.13	$/m2
TZ Mat'l & Install	**$12.50**	$/ft2	134.37	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**9**			
No. TZ per AC	**4**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	8			
A-C distance	26.3	ft	8.0	m
TZ distance	5.3	ft	1.6	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	3,063	yd3	2,346	m3
Soil per TZ	613	yd3	469	m3
Min effl vol reqd per TZ	99,173	gal	375	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	272	gal/d	1.03	m3/d
Total Flowrate req'd	8,695	gal/d	32.93	m3/d
Electric field gradient	**27.1**	volt/m		
Current	1,904	amps		
Total Charge Input	16,683,104	amp-hr		
Applied Potential	**217**	volts		
Power	413	kw		
Total E-field energy	3,617,073	kwh		
Costs				
Field Labor	$30,000			
Electricity	$180,854			
Electrodes & Installation	$524,475		Specific Cost	
Treatment zones	$1,260,000			
Rectifiers	$49,549		93.67	$/yd3
Fixed	$250,000		122.27	$/m3
TOTAL	$2,294,878			

Exhibit 2. Mandrel Tremie Tube (1 Yr, 15 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$16.00**	$/ft2	172.22	$/m2
TZ Mat'l & Install	**$9.50**	$/ft2	102.12	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**7**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	6.6	ft	2.0	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	6,125	yd3	4,692	m3
Soil per TZ	766	yd3	587	m3
Min effl vol reqd per TZ	123,966	gal	469	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	340	gal/d	1.29	m3/d
Total Flowrate req'd	9,510	gal/d	36.02	m3/d
Electric field gradient	**33.9**	volt/m		
Current	1,190	amps		
Total Charge Input	10,426,940	amp-hr		
Applied Potential	**542**	volts		
Power	645	kw		
Total E-field energy	5,651,676	kwh		
Costs				
Field Labor	$30,000			
Electricity	$282,584			
Electrodes & Installation	$252,000		Specific Cost	
Treatment zones	$837,900			
Rectifiers	$77,420		70.61	$/yd3
Fixed	$250,000		92.17	$/m3
TOTAL	$1,729,904			

Exhibit 3. Optimized Emplacement (1 Yr, 15 Ft Treatment Depth)

INPUT PARAMETERS			
Remediation Time and Site Dimensions			
Remediation Time	**1** yr		8760 h
Treatment Depth	15 ft		4.575 m
X (tr length)	210 ft		64.05 m
Y	210 ft		64.05 m
Soil and Contaminant Properties			
No. PV req'd	**2**		2
σ	0.3 mS cm-1		0.03 S m-1
ke	1.50E-05 cm2V-1s-1		0.0000054 m2V-1h-1
n	0.4 m3/m3		0.4
Prices and Fixed Costs			
Rectifiers	120 $/kw		
Electricity	0.05 $/kwh		5.00E-05 $/wh
Electrode Mat'l & Install	**$5.00** $/ft2		53.82 $/m2
TZ Mat'l & Install	**$3.00** $/ft2		32.25 $/m2
Fixed Costs	$250,000		
Field Labor Cost	$30,000 per year		
Electrode & Treatment Zone (TZ) Configuration			
No. electrode rows	**6**		
No. TZ per AC	**8**		
CALCULATIONS			
Intermediate Calculations			
No. electrode regions	5		
A-C distance	42.0 ft		12.8 m
TZ distance	4.7 ft		1.4 m
Soil Amount, Total	24,500 yd3		18,768 m3
Soil per elect pair	4,900 yd3		3,754 m3
Soil per TZ	544 yd3		417 m3
Min effl vol reqd per TZ	88,154 gal		334 m3
Cross-sectional area	3,150 ft2		293 m2
Energy and Flowrate			
Flowrate per TZ	242 gal/d		0.91 m3/d
Total Flowrate req'd	9,661 gal/d		36.59 m3/d
Electric field gradient	**24.1** volt/m		
Current	1,058 amps		
Total Charge Input	9,268,391 amp-hr		
Applied Potential	**308** volts		
Power	326 kw		
Total E-field energy	2,857,934 kwh		
Costs			
Field Labor	$30,000		
Electricity	$142,897		
Electrodes & Installation	$94,500	Specific Cost	
Treatment zones	$378,000		
Rectifiers	$39,150		38.14 $/yd3
Fixed	$250,000		49.79 $/m3
TOTAL	$934,546		

Exhibit 4. Base Case (1 Yr, 45 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$18.50**	$/ft2	199.13	$/m2
TZ Mat'l & Install	**$12.50**	$/ft2	134.37	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**9**			
No. TZ per AC	**4**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	8			
A-C distance	26.3	ft	8.0	m
TZ distance	5.3	ft	1.6	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	9,188	yd3	7,038	m3
Soil per TZ	1,838	yd3	1,408	m3
Min effl vol reqd per TZ	297,519	gal	1,126	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	815	gal/d	3.09	m3/d
Total Flowrate req'd	26,084	gal/d	98.80	m3/d
Electric field gradient	**27.1**	volt/m		
Current	5,713	amps		
Total Charge Input	50,049,311	amp-hr		
Applied Potential	**217**	volts		
Power	1,239	kw		
Total E-field energy	10,851,219	kwh		
Costs				
Field Labor	$30,000			
Electricity	$542,561			
Electrodes & Installation	$1,573,425		Specific Cost	
Treatment zones	$3,780,000			
Rectifiers	$148,647		86.05	$/yd3
Fixed	$250,000		112.33	$/m3
TOTAL	$6,324,633			

Exhibit 5. Mandrel Tremie Tube (1 Yr, 45 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$16.00**	$/ft2	172.22	$/m2
TZ Mat'l & Install	**$9.50**	$/ft2	102.12	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**7**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	6.6	ft	2.0	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	2,297	yd3	1,760	m3
Min effl vol reqd per TZ	371,899	gal	1,408	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	1,019	gal/d	3.86	m3/d
Total Flowrate req'd	28,529	gal/d	108.07	m3/d
Electric field gradient	**33.9**	volt/m		
Current	3,571	amps		
Total Charge Input	31,280,819	amp-hr		
Applied Potential	**542**	volts		
Power	1,936	kw		
Total E-field energy	16,955,029	kwh		
Costs				
Field Labor	$30,000			
Electricity	$847,751			
Electrodes & Installation	$756,000		Specific Cost	
Treatment zones	$2,513,700			
Rectifiers	$232,261		62.99	$/yd3
Fixed	$250,000		82.22	$/m3
TOTAL	$4,629,712			

Exhibit 6. Optimized Emplacement (1 Yr, 45 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**1**	yr	8760	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$5.00**	$/ft2	53.82	$/m2
TZ Mat'l & Install	**$3.00**	$/ft2	32.25	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**6**			
No. TZ per AC	**8**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	5			
A-C distance	42.0	ft	12.8	m
TZ distance	4.7	ft	1.4	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	14,700	yd3	11,261	m3
Soil per TZ	1,633	yd3	1,251	m3
Min effl vol reqd per TZ	264,461	gal	1,001	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	725	gal/d	2.74	m3/d
Total Flowrate req'd	28,982	gal/d	109.78	m3/d
Electric field gradient	**24.1**	volt/m		
Current	3,174	amps		
Total Charge Input	27,805,173	amp-hr		
Applied Potential	**308**	volts		
Power	979	kw		
Total E-field energy	8,573,802	kwh		
Costs				
Field Labor	$30,000			
Electricity	$428,690			
Electrodes & Installation	$283,500		Specific Cost	
Treatment zones	$1,134,000			
Rectifiers	$117,449		30.53	$/yd3
Fixed	$250,000		39.85	$/m3
TOTAL	$2,243,639			

Exhibit 7. Base Case (3 Yrs, 15 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$18.50**	$/ft2	199.13	$/m2
TZ Mat'l & Install	**$12.50**	$/ft2	134.37	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**4**			
No. TZ per AC	**5**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	3			
A-C distance	70.0	ft	21.4	m
TZ distance	11.7	ft	3.6	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	8,167	yd3	6,256	m3
Soil per TZ	1,361	yd3	1,043	m3
Min effl vol reqd per TZ	220,384	gal	834	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	201	gal/d	0.76	m3/d
Total Flowrate req'd	3,019	gal/d	11.44	m3/d
Electric field gradient	**20.1**	volt/m		
Current	529	amps		
Total Charge Input	13,902,586	amp-hr		
Applied Potential	**428**	volts		
Power	227	kw		
Total E-field energy	5,954,029	kwh		
Costs				
Field Labor (Disc. by 12%)	$80,702			
Electricity (Disc. by 12%)	$266,944			
Electrodes & Installation	$233,100		Specific Cost	
Treatment zones	$590,625			
Rectifiers	$27,187		59.12	$/yd3
Fixed	$250,000		77.18	$/m3
TOTAL	$1,448,558			

Exhibit 8. Mandrel Tremie Tube (3 Yrs, 15 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$16.00**	$/ft2	172.22	$/m2
TZ Mat'l & Install	**$9.50**	$/ft2	102.12	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**4**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	10.5	ft	3.2	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	6,125	yd3	4,692	m3
Soil per TZ	1,225	yd3	938	m3
Min effl vol reqd per TZ	198,346	gal	751	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	181	gal/d	0.69	m3/d
Total Flowrate req'd	2,898	gal/d	10.98	m3/d
Electric field gradient	**18.1**	volt/m		
Current	635	amps		
Total Charge Input	16,683,104	amp-hr		
Applied Potential	**289**	volts		
Power	184	kw		
Total E-field energy	4,822,764	kwh		
Costs				
Field Labor (Disc. by 12%)	$80,702			
Electricity (Disc. by 12%)	$216,225			
Electrodes & Installation	$252,000		Specific Cost	
Treatment zones	$478,800			
Rectifiers	$22,022		53.05	$/yd3
Fixed	$250,000		69.25	$/m3
TOTAL	$1,299,748			

Exhibit 9. Optimized Emplacement (3 Yrs, 15 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	15	ft	4.575	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$5.00**	$/ft2	53.82	$/m2
TZ Mat'l & Install	**$3.00**	$/ft2	32.25	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**6**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	7.5	ft	2.3	m
Soil Amount, Total	24,500	yd3	18,768	m3
Soil per elect pair	6,125	yd3	4,692	m3
Soil per TZ	875	yd3	670	m3
Min effl vol reqd per TZ	141,676	gal	536	m3
Cross-sectional area	3,150	ft2	293	m2
Energy and Flowrate				
Flowrate per TZ	129	gal/d	0.49	m3/d
Total Flowrate req'd	3,105	gal/d	11.76	m3/d
Electric field gradient	**12.9**	volt/m		
Current	453	amps		
Total Charge Input	11,916,503	amp-hr		
Applied Potential	**206**	volts		
Power	94	kw		
Total E-field energy	2,460,594	kwh		
Costs				
Field Labor (Disc. by 12%)	$80,702			
Electricity (Disc. by 12%)	$110,319			
Electrodes & Installation	$78,750		Specific Cost	
Treatment zones	$226,800			
Rectifiers	$11,236		30.93	$/yd3
Fixed	$250,000		40.38	$/m3
TOTAL	$757,806			

Exhibit 10. Base Case (3 Yrs, 45 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$18.50**	$/ft2	199.13	$/m2
TZ Mat'l & Install	**$12.50**	$/ft2	134.37	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**4**			
No. TZ per AC	**5**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	3			
A-C distance	70.0	ft	21.4	m
TZ distance	11.7	ft	3.6	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	24,500	yd3	18,768	m3
Soil per TZ	4,083	yd3	3,128	m3
Min effl vol reqd per TZ	661,153	gal	2,502	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	604	gal/d	2.29	m3/d
Total Flowrate req'd	9,057	gal/d	34.31	m3/d
Electric field gradient	**20.1**	volt/m		
Current	1,587	amps		
Total Charge Input	41,707,759	amp-hr		
Applied Potential	**428**	volts		
Power	680	kw		
Total E-field energy	17,862,088	kwh		
Costs				
Field Labor (Disc. by 12%)	$80,702			
Electricity (Disc. by 12%)	$800,832			
Electrodes & Installation	$699,300		Specific Cost	
Treatment zones	$1,771,875			
Rectifiers	$81,562		50.13	$/yd3
Fixed	$250,000		65.43	$/m3
TOTAL	$3,684,271			

Exhibit 11. Mandrel Tremie Tube (3 Yrs, 45 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$16.00**	$/ft2	172.22	$/m2
TZ Mat'l & Install	**$9.50**	$/ft2	102.12	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**4**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	10.5	ft	3.2	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	3,675	yd3	2,815	m3
Min effl vol reqd per TZ	595,038	gal	2,252	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	543	gal/d	2.06	m3/d
Total Flowrate req'd	8,695	gal/d	32.93	m3/d
Electric field gradient	**18.1**	volt/m		
Current	1,904	amps		
Total Charge Input	50,049,311	amp-hr		
Applied Potential	**289**	volts		
Power	551	kw		
Total E-field energy	14,468,291	kwh		
Costs				
Field Labor (Disc. by 12%)	$80,702			
Electricity (Disc. by 12%)	$648,674			
Electrodes & Installation	$756,000		Specific Cost	
Treatment zones	$1,436,400			
Rectifiers	$66,065		44.05	$/yd3
Fixed	$250,000		57.50	$/m3
TOTAL	$3,237,841			

Exhibit 12. Optimized Emplacement (3 Yrs, 45 Ft Treatment Depth)

INPUT PARAMETERS				
Remediation Time and Site Dimensions				
Remediation Time	**3**	yr	26280	h
Treatment Depth	45	ft	13.725	m
X (tr length)	210	ft	64.05	m
Y	210	ft	64.05	m
Soil and Contaminant Properties				
No. PV req'd	**2**		2	
σ	0.3	mS cm-1	0.03	S m-1
ke	1.50E-05	cm2V-1s-1	0.0000054	m2V-1h-1
n	0.4	m3/m3	0.4	
Prices and Fixed Costs				
Rectifiers	120	$/kw		
Electricity	0.05	$/kwh	5.00E-05	$/wh
Electrode Mat'l & Install	**$5.00**	$/ft2	53.82	$/m2
TZ Mat'l & Install	**$3.00**	$/ft2	32.25	$/m2
Fixed Costs	$250,000			
Field Labor Cost	$30,000	per year		
Electrode & Treatment Zone (TZ) Configuration				
No. electrode rows	**5**			
No. TZ per AC	**6**			
CALCULATIONS				
Intermediate Calculations				
No. electrode regions	4			
A-C distance	52.5	ft	16.0	m
TZ distance	7.5	ft	2.3	m
Soil Amount, Total	73,500	yd3	56,305	m3
Soil per elect pair	18,375	yd3	14,076	m3
Soil per TZ	2,625	yd3	2,011	m3
Min effl vol reqd per TZ	425,027	gal	1,609	m3
Cross-sectional area	9,450	ft2	879	m2
Energy and Flowrate				
Flowrate per TZ	388	gal/d	1.47	m3/d
Total Flowrate req'd	9,316	gal/d	35.29	m3/d
Electric field gradient	**12.9**	volt/m		
Current	1,360	amps		
Total Charge Input	35,749,508	amp-hr		
Applied Potential	**206**	volts		
Power	281	kw		
Total E-field energy	7,381,781	kwh		
Costs				
Field Labor (Disc. by 12%)	$80,702			
Electricity (Disc. by 12%)	$330,956			
Electrodes & Installation	$236,250		Specific Cost	
Treatment zones	$680,400			
Rectifiers	$33,707		21.93	$/yd3
Fixed	$250,000		28.63	$/m3
TOTAL	$1,612,014			